

Integrated Hydrological Modelling over Upstream Catchments of Himalayan Rivers and Assessment of Hydrological Events in Tehri Dam and Srinagar Catchments [†]

V. Sivashankari ^{1,*}, Amit Kumar Dubey ², K. Nivedita Priyadarshini ¹ and Sulochana Shekhar ¹

¹ Department of Geography, School of Earth Sciences, Central University of Tamil Nadu, Thiruvavur 610005, Tamil Nadu, India; nivi.darshini@yahoo.com (K.N.P.); sulochana@cutn.ac.in (S.S.)

² Space Applications Centre, Environment and Hydrology, Ahmedabad 380015, India; a_dubey@sac.isro.gov.in

* Correspondence: shivaavettri@gmail.com; Tel.: +91-960-024-1370

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Abstract: Flash floods in the Himalayan Rivers result in hundreds of deaths causing a sudden hazard in a minimum period of time. These hydrological events of mostly happen due to cloudburst incidents in the Indian Himalayas, with an unexpected heavy overwhelming of precipitation in a short interval over a small region. These extreme hydrological events are assessed through the analytical hierarchy process for the upper stream catchments of Tehri Dam and Srinagar. The morphometry characteristics of these catchments are collaboratively integrated with the SAC (Space Application Centre) hydro simulated discharge and rainfall data to identify the flash-flood-vulnerable hazard region over the surrounding catchment regions.

Keywords: flash floods; cloudburst; hydrological events; Analytical Hierarchy Process

1. Introduction

The eventuality of natural disasters associated with water, particularly flash floods, is a common phenomenon in the hilly part of the Indian Himalayas. The overwhelming of water in these hilly mountains is greater than the usual level, with some specific reasons of cloudburst in the catchment zone, and vigorous and lengthened rainfall causing the obstruction of river channels which induce the sudden breakage of artificial/natural lakes [1]. The cloudburst incidents are associated with the unusual steep slopes and bad inclines of the Himalayan orography, making the ultimate platform for flash flood activities. Even though advanced techniques have arisen, the prediction of these catastrophic occurrences remains unpredictable one [2]. The morphometry characteristics of the catchments enact the hydrological processes, in addition to observed parameters of discharge and intense rainfall data over the flash-flood-liable zones. The morphometric estimation of the drainage network helps to learn the behavioral characteristics of the drainage network and their impact on the flood-prone areas [3,4]. Drainage basins are delineated with a digital elevation model, and stream number and stream orders are computed by Strahler theory in order to assess flash flood vulnerability [5]. To understand the catchment response to hydrological events, various flood-deriving parameters in morphometry analysis including rainfall, slope, drainage density, land use, etc., are predominantly assessed for flood hazards. However, there is difficulty in getting spatial prediction data from various sources due to inappropriate handling. The research on GIS tools

reveals that flow direction, flow accumulation, precipitation, and drainage are some parameters for flooding events. These parameters are weighted by priority based on Saaty's nine-point scale and analyzed with the model of analytical hierarchy Process (AHP) [6,7]. The paper concentrates on the mapping of flood-vulnerable areas which are highly correlated in the Indian Himalayan rivers where the flash floods and cloudburst are common incidents. The decision-making techniques are used to understand this complex issue via analytical hierarchy process. The main objectives of this paper are to identify flood-vulnerable areas by the following steps:

1. Analysis of morphometry parameters using shuttle radar topography mission (SRTM) DEM integrated with discharge and rainfall data from SAC hydro model.
2. Normalization of these parametric classified values via analytical hierarchy process by assigning priority weight to each parameter.

2. Materials and Methods

2.1. Study Area

The study area Figure 1 shows Tehri Dam catchment is in the deep of Garhwal hills of Uttarakhand, includes the rivers Bhagirathi and Bhilangana, and is at the extent of 30.3781° N latitude and 78.4804° E longitude. The Srinagar catchment is extended at the latitude of 30.2247° N and longitude of 78.7986° E, and has a major tributary of the Ganga river basin flowing through it, named Alaknanda.

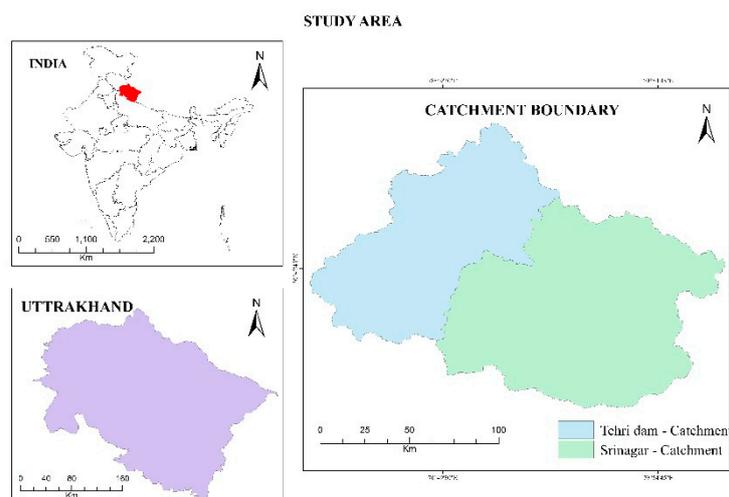


Figure 1. Location of the study area.

2.2. Datasets

The goals of this research paper were achieved by data gathered from different sources. Different GIS layers were created for the study area catchments. Shuttle radar topography mission (SRTM) DEM at the spatial resolution of 30 m was used for the determination of morphometric characteristics of the catchments, namely drainage density, slope, relief ratio and stream frequency, by delineating the catchment boundary regions. The SRTM DEM was used for the generation of the slope map and to produce hillshade regions along the catchment boundary. To study the catchment surface forms and their importance, these quantitative approaches of slope evaluation were used [8]. SAC hydro model, developed by Space Application Centre, Ahmedabad, provided daily average and accumulated discharge and rainfall data for India at a 5 km resolution. These datasets were gathered and incorporated in this study, and study area data were extracted using ArcGIS 10.5 software (Esri, Redlands, CA, USA). The National Resource Database (NRDB) was used to acquire a geological layer at the scale of 1:250,000.

2.3. Methodology

The methodology in Figure 2 involved determining the causative parameters for flooding occurring in the study region catchments and finally, these causative criteria were put into the analytical hierarchy process to evaluate flood-susceptible zonation in the catchments.

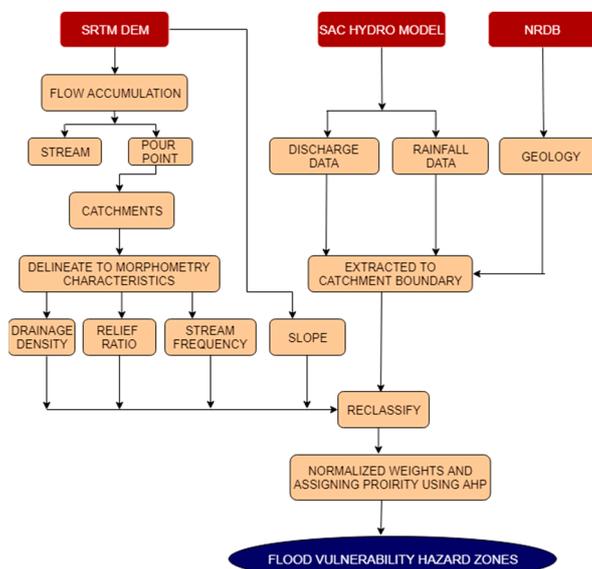


Figure 2. Flowchart for flood hazard zones.

2.3.1. Development of Catchment Morphometry

The two catchment morphometric parameters were inferred by using the linear, areal and relief characteristics. In this study, drainage density, relief ratio, and stream frequency are assessed to achieve the vulnerability assessment of two catchments [9]. Table 1 displays the calculations of catchment morphometry responses.

Table 1. Catchment morphometry parameters.

Category	Parameter	Derivation Procedure
Areal	Drainage Density	$DD = \Sigma L/A$; where DD = drainage density, ΣL = sum of all stream lengths, and A = catchment area (Horton 1932)
Areal	Stream Frequency	$F_s = N_u / A$; F_s = stream frequency, N_u = total length of stream, and A = catchment area (Horton, 1945)
Relief	Relief Ratio	$Rh = H/L$; where Rh = relief ratio, H = horizontal distance along the longest dimension in parallel to drainage line, and L = length of the catchment (Schumm, 1956)

2.3.2. Analytical Hierarchy Process

Analytical hierarchy process (AHP) provides a systematic approach for assessing and merging various factors to support the decision-making technique for various assessments, both qualitative and quantitative. This AHP technique helps to achieve the assessment of various factors and to solve the complex problems of overlapping and combined issues between multiple criteria factors. [10]. This framework was proposed and developed by Saaty’s nine-point scale in 1980 for the decision-making process. The degree of consistency is solved by the consistency ratio (CR) and this CR should be less than or equal to 0.10 to imply that the pairwise matrix is acceptable.

3. Results and Discussion

3.1. Pair-Wise Comparison Matrix for Multi-Criteria and Its Consistency

The pair-wise comparison matrix weighted the various parameters and found alternatives using absolute numbers of 1 to 9 in scale value of AHP. The weights were estimated by Microsoft Excel and priority index values were assigned to each parameter. Hence, the results contain relative weights of C1 = discharge, C2 = rainfall, C3 = slope, C4 = drainage density, C5 = geology, C6 = relief ratio, and C7 = stream frequency, as shown in Table 2. Therefore, the results were incorporated into the ArcGIS 10.5 software (Esri, Redlands, CA, USA) to identify the flood-vulnerable hazard zones over the catchment region [11].

Table 2. Pair-wise comparison matrix and its relative weight.

Parameters	C1	C2	C3	C4	C5	C6	C7	Mean	Weight (%)
C1	0.53	0.72	0.64	0.42	0.48	0.36	0.33	0.50	50
C2	0.07	0.09	0.16	0.17	0.14	0.18	0.17	0.14	14
C3	0.07	0.05	0.08	0.17	0.14	0.18	0.21	0.13	13
C4	0.11	0.05	0.04	0.08	0.10	0.09	0.08	0.08	8
C5	0.08	0.05	0.04	0.06	0.07	0.09	0.08	0.07	7
C6	0.09	0.03	0.03	0.06	0.05	0.06	0.08	0.06	6
C7	0.07	0.02	0.02	0.04	0.03	0.03	0.04	0.04	4

3.2. Consistency Check

The consistency of the pair-wise matrix was evaluated by the following index: $CR = CI/RI$, where CR = consistency ratio, CI = consistency index, and RI = random index (the values were assigned as shown in Table 3).

Table 3. Random index value.

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

AHP theory indicates that the thumb-rule set of consistency ratio (CR) must be less than or equal to 0.1. For this, foremost the consistency index is to be calculated using the following equation:

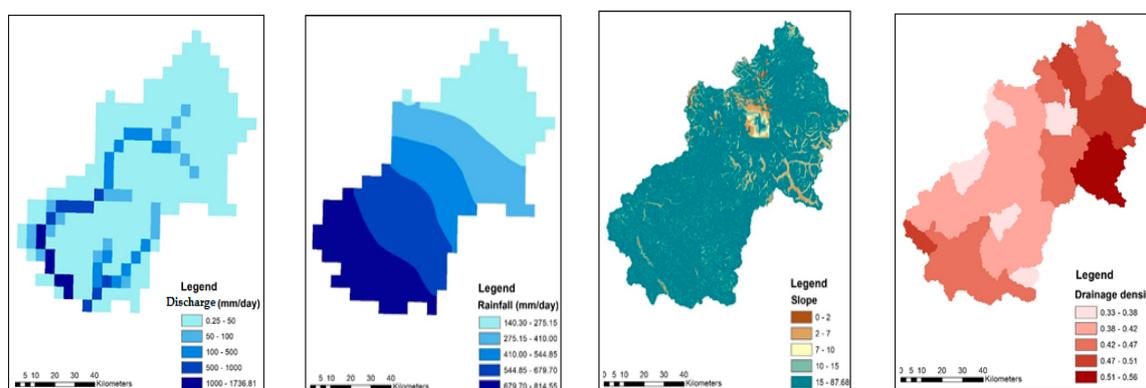
$$CI = (\lambda_{max} - n)/(n - 1). \tag{1}$$

From Table 1, $\lambda_{max} = 7.36$, $n = 7$ (No. of parameters we used), then, $CI = (7.36 - 7)/(7 - 1) = 0.061$ which is less than 0.1. Since CR's value is lower than the threshold (0.1) the weights' consistency is affirmed.

For every parameter, the ranges were classified and the index value was assigned based on the vulnerability characteristics as shown in Table 4. Every layer was reclassified with their range value and their index value was multiplied by their range value, then layers were again reclassified with the index value as shown in map of Figures 3 and 4. Once the weight in each factor was determined, the multi-criteria analysis was performed to produce a flood-vulnerable area by using the GIS approach. To compute the vulnerable area, a weight linear combination was applied as shown in the following equation: $Z = (50 \times \text{discharge}) + (14 \times \text{rainfall}) + (13 \times \text{slope}) + (8 \times \text{drainage density}) + (7 \times \text{geology}) + (6 \times \text{relief ratio}) + (4 \times \text{stream frequency})$.

Table 4. Multi-criteria decision analysis for Tehri Dam and Srinagar catchment.

Factor	Tehri Dam Catchment		Srinagar Catchment		Weight
	Criteria	Index	Criteria	Index	
Discharge (m³/s)	0.01–50	0.05	0.25–50	0.05	50%
	50–100	0.09	50–100	0.10	
	100–500	0.16	100–500	0.13	
	500–1000	0.26	500–1000	0.28	
	1000–1749.02	0.45	1000–1736.81	0.44	
Rainfall (mm/day)	62–189	0.04	140.3–275.15	0.05	14%
	189–316	0.09	275.15–410	0.11	
	316–443	0.15	410–544.85	0.16	
	443–570	0.31	544.85–679.7	0.29	
	570–697	0.40	679.7–814.5	0.40	
Slope (%)	0–2	0.43	0–2	0.45	13%
	2–7	0.28	2–7	0.27	
	7–10	0.15	7–10	0.15	
	10–15	0.09	10–15	0.09	
	15–81.76	0.05	15–87.56	0.05	
Drainage Density	0.36–0.39	0.05	0.34–0.38	0.05	8%
	0.39–0.41	0.10	0.38–0.43	0.12	
	0.41–0.43	0.18	0.43–0.47	0.15	
	0.43–0.45	0.24	0.47–0.52	0.26	
	0.45–0.48	0.43	0.52–0.56	0.42	
Geology	Sandy Loam	0.66	Sandy	0.66	7%
	Sandy	0.22	Sandy Loam	0.22	
	Snow/other	0.12	Snow/other	0.12	
Relief Ratio	0.05–0.12	0.43	0.04–0.09	0.43	6%
	0.12–0.18	0.29	0.09–0.13	0.28	
	0.18–0.24	0.15	0.13–0.17	0.16	
	0.24–0.30	0.08	0.17–0.21	0.08	
	0.30–0.36	0.05	0.21–0.26	0.05	
Stream Frequency	0.18–0.20	0.05	0.16–0.19	0.05	4%
	0.20–0.22	0.10	0.19–0.22	0.10	
	0.22–0.24	0.19	0.22–0.25	0.19	
	0.24–0.25	0.26	0.25–0.27	0.25	
	0.25–0.27	0.41	0.27–0.30	0.40	



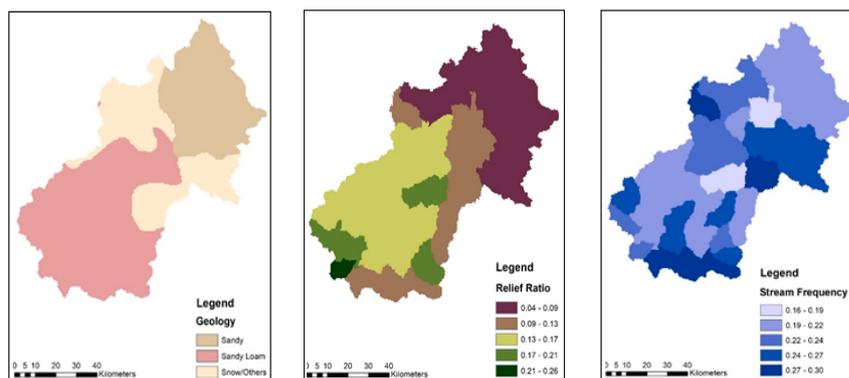


Figure 3. Multi-criteria parameter maps of Tehri Dam catchment.

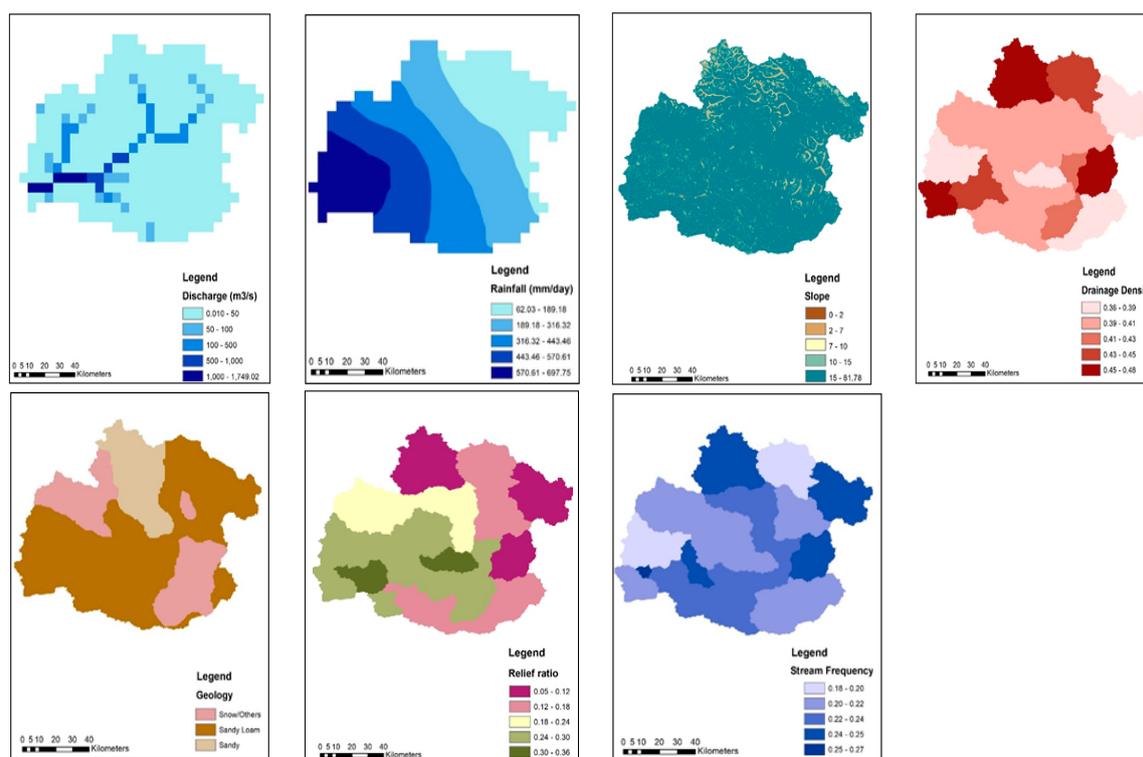


Figure 4. Multi-criteria parameter maps of Srinagar catchment.

The final vulnerability map output has been represented in Figure 5 with a graduated scale of a color map indicating the flood vulnerability. The vulnerability of flood areas was categorized into five criteria, namely “very high vulnerability”, “high vulnerability”, “moderate vulnerability”, “low vulnerability”, and “very low vulnerability”.

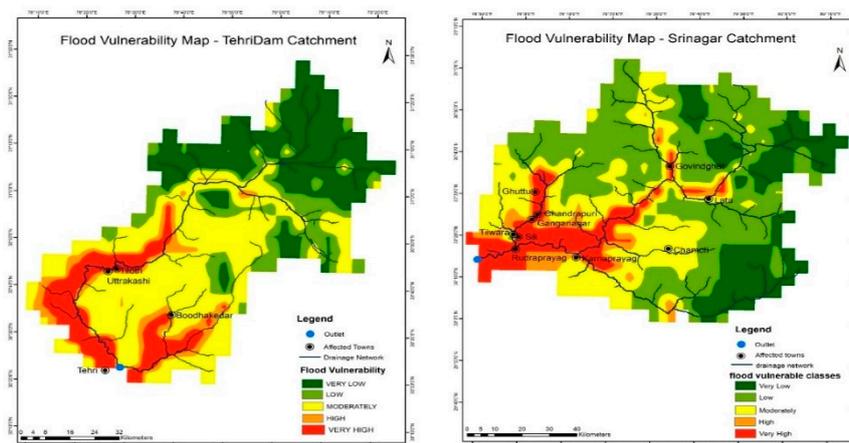


Figure 5. Flood vulnerability hazard zone map.

3.3. Flood Hazard Area Estimation

The above flood vulnerability hazard map (Figure 5) shows the range of vulnerable areas, with areas which are very highly prone to flash floods indicated as red zones. Generally, it is clearly seen that very high to highly prone areas are very close to the river Bhagirathi and the river Bhilanganga. The sudden flash flood causes a dramatic increase in river water level and creates a hazard to the livelihood of people in proximity to the river. The vulnerability area is calculated and shown in Table 5.

Table 5. Area calculation for the study area catchments.

Vulnerable Class	Tehri Dam Catchment		Srinagar Catchment	
	Area (km ²)	Area (%)	Area (km ²)	Area (%)
	Total Area = 7294.78 km		Total Area = 10,554 km	
Very Low	2000.24	30%	1775.52	18%
Low	800.1	12%	3875.47	40%
Moderate	2775.34	41%	2450.30	25%
High	425.05	6%	525.06	5%
Very High	750.09	11%	1050.13	11%

4. Conclusions

The assessment of flash flood hazard zone maps is necessary for identifying very highly prone areas where extreme weather events often happen. The final priority assessment map shows a clear-cut decision on where flash floods can make a sudden and strong impact. The systematic approach of AHP helps to determine various criteria analyses, made at one time to produce the output results. In addition, the consistency ratio of the pair-wise comparison matrix is 0.06 which is acceptable at the thumb-rule set. Although the very highly prone areas show a relatively low area, the places where they are estimated are very close to the river line level. These catchments show very high vulnerability in the downstream region where the floods are accumulated and discharged. Future work will be carried out to determine the flash flood hazard zones in all Himalayan catchments.

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